



Battery Capacity

Discharge

You can't do much to improve battery design. You can, however, do your best to understand their chemistry, how they work, and how they behave under various loads. Ed focuses on the discharge portion of the battery cycle.

We devote rapt attention to the circuitry and software in electronic devices, because that's the "fun stuff" we enjoy working with. Unfortunately, batteries form the weak link in most gizmos: without batteries, nothing else works! Even with the best batteries inside, the device's run time, performance, and cost may not reach your expectations.

While we can't do much to improve battery design, we can make the best of what's available. That often requires looking beyond the facts that everyone knows to find the truth of the matter, so I'll take a detailed look at the sometimes surprising performance of common batteries. I'll concentrate on the discharge part of the battery cycle in this column and save charging for the April issue.

ALKALINE AA: THE BASICS

Alkaline AA cells are the ones everybody loves to hate, because they're good enough and cheap enough to make everything else look bad. Indeed, a device powered by AA alkaline cells can run on power bought in any open-air, dirt-floor market in the world. Try to find a fancy lithium-ion photo battery in the same place, let alone compatible AC for your recharger, and you'll get the message.

Figure 1 shows the discharge curves for four brand-name alkaline cells from the same lot. The graph shows the relation between the cell voltage (on the vertical axis) and the cumulative energy drawn from it (on the

horizontal axis).

For example, the top curve shows that a 100-mA load will initially see about 1.6 V, which then stabilizes around 1.1 V during the middle of the curve and then drops abruptly after the battery has delivered about 2.2 A·h. The test ended at 0.4 V after 2.5 A·h.

The horizontal axis uses ampere-hour units, rather than time, to simplify energy comparisons. My battery tester applies a constant-current load and records the voltage as a function of the elapsed time in seconds, so the conversion is:

$$\text{A}\cdot\text{h} = \frac{\text{amperes} \times \text{seconds}}{3,600}$$

Converting units in the other direction is equally easy: a cell that delivers 2.5 A·h at 100 mA lasts for:

$$25 \text{ h} = \frac{2.5 \text{ A}\cdot\text{h}}{0.1 \text{ A}}$$

That's 90 kiloseconds, if you prefer hard metric units, and should give some indication why I don't present discharge curves for lower currents.

The lower trace shows that alkaline cells behave poorly in high-current devices: a 1-A load draws about 0.8 A·h from the cell, only a third of the energy delivered during the 100-mA test. An alkaline cell would last only 0.8 h or 48 min. in that application!

The endpoint voltage depends on your gizmo's specifications. I chose 0.4 V to draw the maximum energy from the cells, but a device requiring a higher voltage will draw less energy

from the cell before failing.

A 0.8-V endpoint delivers nearly the same 2.5 A·h at 100 mA, but only 0.3 A·h at 1 A. The unwary designer who assumes a "1.5 V" alkaline cell will be all used up at 1.0 V is in for a rude surprise: at 1 A, the cell fails in 6 min. after delivering just 0.1 A·h!

Fairly obviously, alkaline cells work best in low-current devices that must operate for prolonged periods, particularly at room temperature. As you'll see, they have a surprisingly high capacity compared to more modern technologies.

Incidentally, the obvious glitches in Figure 1's brown 250-mA trace came from a failing alligator clip. I used heavy-duty bulldog clips or crimped-and-soldered connections for the remaining tests and had no further troubles. My West Mountain Radio Computerized Battery Analyzer has excellent, low-resistance Anderson Powerpole connectors, but the battery termination is obviously out of their control.

NiMH: THE CONTENDER

Alkalines have the severe disadvantage that they're primary, non-rechargeable cells. Nickel-metal hydride cells, the next step up, are secondary cells that can be recharged "up to 1,000 times!" At least, that's what the ads claim, anyway. The reality is that NiMH cells have their own set of trade-offs.

Figure 2 shows discharge curves for a single 2 A·h AA cell at the same

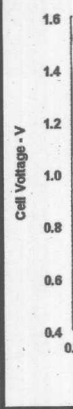


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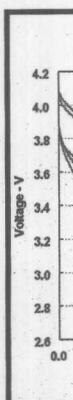


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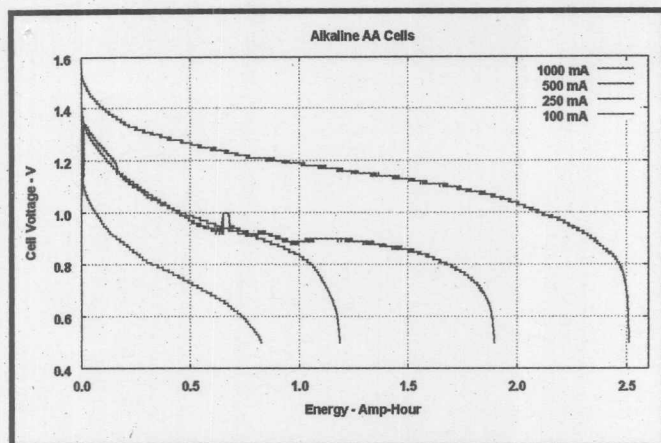


Figure 1—Those familiar AA alkaline cells behave surprisingly well at low discharge rates, but high internal resistance limits their usefulness in high-current gizmos. A bad alligator clip caused the glitches in the 250-mA trace.

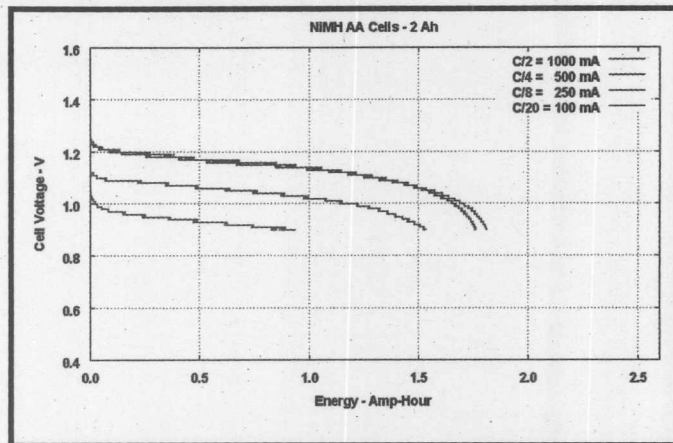


Figure 2—AA Nickel-metal hydride cells have lower voltage and capacity, but much better high-current performance. Yes, the cell discharged at 250 mA barely outlived the one at 100 mA, but that may be due to a different starting charge or sheer perversity.

scale as Figure 1. Two essential facts stand out: lower overall energy capacity and better high-current performance!

Although the cell delivered nearly its total rated capacity at lower discharge rates, it may come as a surprise that even high-capacity NiMH cells deliver less total energy than cheap, disposable alkaline cells. The 100 mA trace in Figure 2 seems low, although that may be a slight variation in the starting charge level. We'll see an example of that with a NiCd cell later on.

I stopped the NiMH tests at 0.9 V, rather than 0.4 V, because that's the recommended per-cell endpoint voltage for multi-cell packs. Although you can discharge single cells to lower voltages, the shape of the curves shows that you don't get that much additional energy. Worse, over-discharging a pack can ruin it, as you'll

also see later in this column.

A cell's high-current performance obviously depends on its internal resistance. That value doesn't appear on the label, but you can get a good approximation to a cell's internal resistance by measuring its terminal voltage at different currents. The internal resistance generally increases as the cell discharges, which means you get lower output voltage for a given current over the life of the cell.

For example, the alkaline cells in Figure 1 have an initial internal resistance of:

$$0.4 \Omega = \left| \frac{1.55 - 1.15 \text{ V}}{0.1 - 1.0 \text{ A}} \right|$$

At the endpoint of the 1.0-A current curve, the resistance has doubled to:

$$0.8 \Omega = \left| \frac{1.2 - 0.5 \text{ V}}{0.1 - 1.0 \text{ A}} \right|$$

The NiMH cell shows internal resistances of 0.2 and 0.3 Ω under similar conditions. Note that the NiMH cell delivers more total energy than the alkaline cell at 1 A, despite the higher endpoint voltage, in contrast to its performance at lower current.

Cells also display an AC impedance that may be much higher than the resistance in applications that deliver

AC power. If you're designing RF transmitters, in particular, pay attention to supply decoupling and filtering, because batteries are definitely not perfect voltage sources.

A cell's energy capacity is denoted as "C" (not to be confused with C-size cylindrical cells) and cell currents are generally given as fractions or multiples of that numerical value in amperes. A 1-A discharge current is a "C/2" rate for those NiMH cells and slightly less for the alkalines.

As a rule of thumb, charge or discharge currents exceeding C/2 require careful consideration of temperatures, voltages, and external circuitry to prevent damage. In any event, alkaline and NiMH cells have sufficiently high internal resistance to prevent discharge currents much beyond 2C, at least for non-pulsed applications.

When you're using loose AA cells in a high-power system, you must also consider the current-carrying capacity of the battery contacts and the interconnections, as I discussed back in my June 2002 column ("Invisible Components," *Circuit Cellar* 143).

LITHIUM ION: THE PRETENDER

Figure 3 shows discharge curves for four lithium-ion battery packs that fit my old Sony DSC-F505V camera. The two oldest batteries (with two sub-AA Li-Ion cells in parallel) produced the lowest curves and, because the camera determines the remaining charge by measuring the terminal voltage, they provide only a few minutes of service.

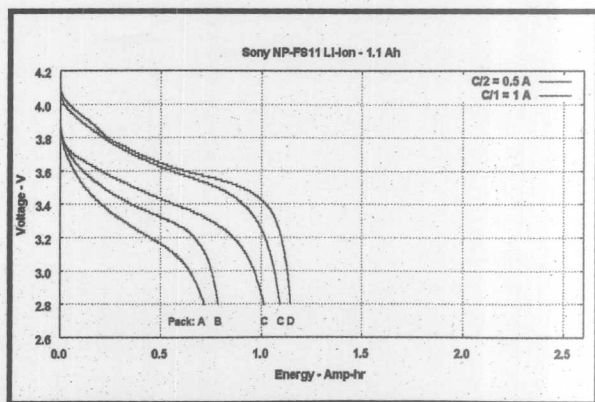


Figure 3—Two older lithium-ion batteries for my Sony DSC-F505V camera produce a "Low Battery" warning almost instantly. Two traces for pack C show the high internal resistance. The voltage axis covers a different range than the other figures, corresponding to Li-Ion's much higher per-cell voltage.

The other two batteries are newer and deliver their rated 1.1 A-h capacity even at a C/2 discharge. In actual use, they last for perhaps 45 min., which simply shows that the camera really needs a higher-capacity battery.

Indeed, my next-generation Sony DSC-717 camera has a much larger battery pack that powers it for 3 h, despite a nearly identical 1.2-A-h rating. The difference is that the 717's battery has two Li-Ion cells in series to provide 7.2 V. Assuming that the two cameras have roughly equivalent power consumption, the newer pack can supply half the current and, thus, should last more than twice as long.

I'm reluctant to abuse these packs, as genuine Sony NP-FS11 packs cost upwards of \$50, but the middle trace in Figure 3 shows the result of a C/1 =

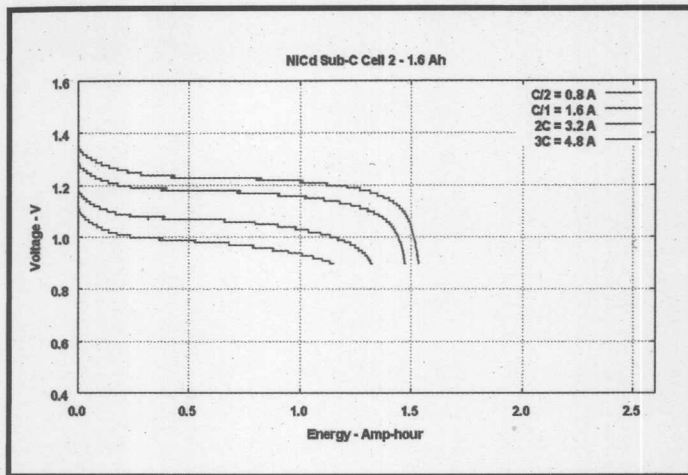


Figure 4—Sub-C nickel-cadmium cells have lower energy storage than AA NiMH cells, despite being physically larger. Their lower internal resistance provides correspondingly higher current capacity, making them valuable for niche applications.

1 A discharge applied to pack C. It delivers nearly its rated capacity, but its internal resistance near the middle of the curves works out to:

$$0.4 \Omega = \frac{3.6 - 3.4 \text{ V}}{0.5 - 1 \text{ A}}$$

Note that the curves aren't particu-

larly flat, showing that the voltage changes dramatically as the battery discharges. I decided not to perform a 2C test, because the C/1 discharge heated the pack more than I expected.

Note that Li-Ion cells provide a third of the energy of alkalines and half that of NiMH, at least for low currents, despite being roughly the same size and shape as two AA cells. Lithium cells have higher energy density on a weight basis, but their key advantage is their ability to be shaped into flat

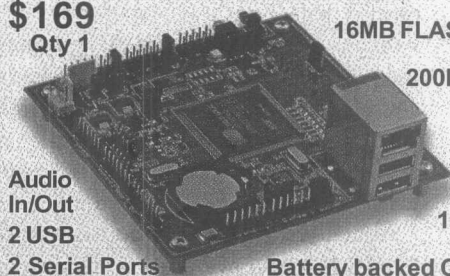
packs or formed around internal components, a trick that's not feasible with loose cells.

Ni-Cd: THE POWERHOUSE

Nickel-cadmium cells, formerly the mainstay of portable devices, now appear only in high-power, high-current

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portable power tools. The reason is simple: the only advantage NiCd cells have over the competition is lower internal resistance. In all other measures, notably energy density and toxicity, they fall short.

Figure 4 shows discharge curves for a single sub-C NiCd cell. I used the same axes as in Figures 1 and 2 to highlight the differences, but with much higher discharge rates.

At 0.5 A-h the internal resistance is about:

$$0.06 \Omega = \frac{1.22 - 0.99 \text{ V}}{0.8 - 4.8 \text{ A}}$$

That's a quarter of the NiMH resistance and nearly an order of magnitude less than alkalines! The resistance increases only slightly during the entire discharge cycle, so the cells can deliver consistently high current.

Because this sub-C cell is physical-

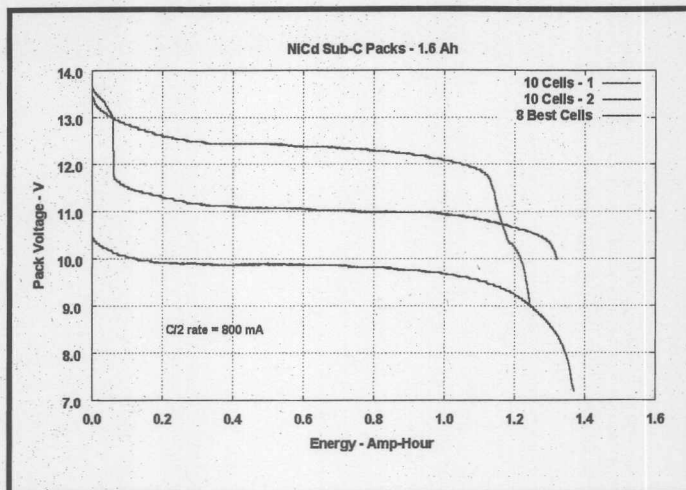


Figure 5—The first decline at the end of the blue trace follows one cell discharging through 0 V. The abrupt drop in the purple trace shows that cell was not fully recharged. The eight best cells worked fine, though, as shown in the brown trace.

ly larger than the AA cells that produced Figures 1 and 2, the lower resistance has two components: a larger electrode area and different chemistry. However, if you're designing a gizmo that must use NiCd cells, you'll probably need larger cells to get enough capacity, which will permit even higher discharge rates.

Because of their low internal resistance, NiCd battery packs can produce staggeringly high short-circuit currents: circuit breakers or fuses aren't just a good idea, they're essential! Pay attention to the cell connections within the battery to reduce the risk of inter-cell shorts.

Outside the pack, ordinary spring-contact battery compartments may not have the low and consistent resistance required to deliver high current to the load. Even at the relatively low 4.8 A I used, two bulldog clips can drop 100 mV: that's 10% of one cell's contribution to the pack's output! High-pressure slip-fit connectors provide low resistance while requiring careful attention to mechanical design.

PACKS: DEATH THROES

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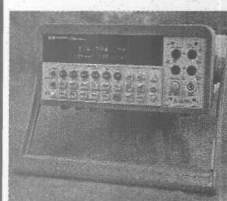
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inside a battery pack provides higher voltage and delivers more power at the same current. The pack's total energy is the sum of the individual cells, but it has the same A-h rating as each cell because the same current passes through each one.

All of the cells in a pack should be identical, but in real life that does not happen. Figure 5 shows the death of a battery pack when the weakest cell fails.

The pack was a watertight case containing 10 1.6 A-h sub-C NiCd cells with an integral C/2 charger. It was a "New Old Stock" surplus item that had been built for a failed product line and, presumably, never used. I figured out how the charger worked, charged the pack, and then measured the pack's performance.

The blue trace seems normal out to about 1.1 A-h, at which point one of the cells was completely discharged and its voltage dropped to zero. Almost immediately another cell discharged and, with two dead cells, the pack reached 9.0 V and the test ended. The pack delivered somewhat less than its rated 1.6 A-h, but with at least one weak cell, it's in bad shape.

The purple trace shows the result after recharging the pack. The weakest cell evidently did not receive a full charge and dropped to 0 V almost immediately. For the remainder of the test, that cell was "reverse charging" and producing hydrogen gas. NiCd cells can contain a limited amount of hydrogen gas under those conditions and it probably didn't vent the gas into the sealed enclosure, but you shouldn't treat your batteries like that. I terminated the test at 10 V, a more conservative 1 V/cell value, because I wanted to prevent any further damage.

I removed the two weakest cells and the charger, manually charged the remaining eight cells, and the brown trace shows that they work fine with about 1.4 A-h of energy. Because NiCd cells improve after a few charge-discharge cycles, these cells will play nicely together as a 9.6-V pack powering the HT on my bike.

Contrary to what you might think,

the weakest cell isn't dead and, in fact, produced Figure 4. Its first solo charge cycle, though, was a bit of a challenge, but that's a subject for the next column.

CONTACT RELEASE

I produced the discharge curves for this column with a West Mountain Radio Computerized Battery Analyzer (CBA). It's basically a power FET mounted on a fan-cooled heatsink, a voltmeter, and an ammeter, all USB-interfaced to a logging program. I wish it had Kelvin voltage sensing and a Linux driver, but it works well enough.

The CBA records one data point per second, producing huge files that choke spreadsheet programs. I used Gnuplot to produce these graphs, with Bash scripts feeding it the commands for each figure. The details are in this column's downloadable files. ☐

Ed Nisley is an EE and author in Poughkeepsie, NY. You may contact him at ed.nisley@ieee.org with "Circuit Cellar" in the subject to avoid spam filters.

PROJECT FILES

To download the Graphs, Gnuplot scripts, etc., go to ftp://ftp.circuitcellar.com/pub/Circuit_Cellar/2007/199.

RESOURCES

Exhaustive NiCd information, www.rcbatteryclinic.com/seminar.htm.

Excellent battery comparison, www.buchmann.ca/Article4-Page1.asp.

SOURCES

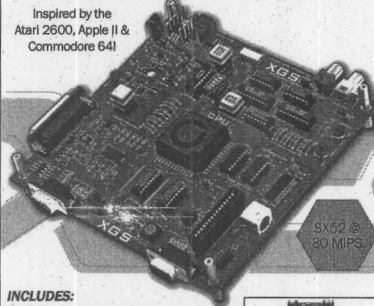
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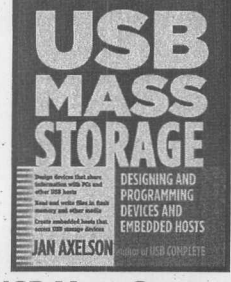
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